Aperture Synthesis Imaging of the Circumstellar Dust Disk Around DO Tauri

1). w. Koerner

169-506, Jet Propulsion laboratory, 4800 Oak Grove 1)r., Pasadena, CA 91109

C. J. Chandler

National Radio Astronomy Observatory, 1'. (). Box (), Socorro, NM 87801

and

A. 1. Sargent

Division of Physics, Mathematics and Astronomy, 105-24, California Institute of Technology, Pasadena, ('A 91125

Received ________________________, accepted ________________________

ABSTRACT

We have detected the T Tauri star, DO Tauri, in a 0.6″-resolution VLA map of 43.3 GHz ($\lambda = 7$ mm) continuum emission. Upper limits to the flux densities at 8.4 and 22.5 GHz limit the contribution of free-free emission due to a compact ionized wind to less than 49%. A power-law fit to our continuum measurements from 43.3 to 232.0 GHz yields a spectral index, α, of 2.39±0.23 for the continuum emission, where $F_\nu \propto \nu^\alpha$. This confirms that the 43.3 GHz emission is thermal radiation from circumstellar dust and leads to a dust emissivity index, β, of 0.39±0.23, if the emission is optically thin. Fitting a model of a thin circumstellar disk to the observed spectral energy distribution results in $\beta = 0.6 \pm 0.3$, consistent with the power-law derivation. This emissivity index for dust in a circumstellar disk around a young T Tauri star is substantially lower than is typical for the interstellar medium and may imply a short formation time for mm-size grains.

Subject headings: stars: individual: DO Tauri — stars: formation — circumstellar matter — planetary systems

1. Introduction

At least 50% of T Tauri stars (TTs) appear to be surrounded by circumstellar dust disks (Strom et al. 1989; Beckwith et al. 1990, hereafter BSCG; André & Montmerle 1994; Henning & Thamm 1994; Osterloh & Beckwith 1995). Global disk properties can be inferred from models of spectral energy distributions (SED) from infrared to millimeter wavelengths (Adams, Lada, & Shu 1987; Beckwith & Sargent 1993; Mannings & Emerson 1994). Masses and sizes are similar to those assumed for the early solar nebula, suggesting that the disks may be protoplanetary (cf. BSCG; Beckwith & Sargent 1993).

The models rely on assumptions about disk morphology and radial structure, and about the nature of the constituent dust grains. Sub-arcsecond resolution is necessary to image the disks directly and measure properties on spatial scales of $\lesssim$100 AU at the distance of the nearest star-forming regions (140 pc). Grain size and composition in these potentially planet-forming disks can be inferred by determining the spectral index, β, of the grain opacity (cf. Pollack et al. 1994) when thermal radiation from dust particles in the disk is optically thin. At wavelengths longer than 3mm, the emission is likely to be optically thin and is well into the Rayleigh-Jeans part of the Planck curve. Although dust continuum radiation has been detected from a number of TTs at $\lambda = 3$ mm (Sargent & Beckwith 1993 and references therein), no thermal emission has been detected unambiguously at longer wavelengths (Mundy et al. 1993). The required spatial resolution and mJy sensitivities can now be achieved using the VLA at wavelengths of 7 mm and beyond.

DO Tauri is a young ($\sim 6.0 \times 10^5$ yrs), low-mass ($\sim 0.7\, M_\odot$), TTs in the Taurus star formation complex at a distance of 140 pc. The SED is consistent with the presence of a $\sim 0.01\, M_\odot$ circumstellar disk (BSCG; Beckwith & Sargent 1991, hereafter BS; Mannings & Emerson 1994). Asymmetric, blue-shifted, [O I] and [S II] forbidden line emission (Appenzeller, Jankovics & Östreicher 1984; Edwards et al. 1987; Edwards, Ray & Mundt

1993) is resolved as an optical jet at PA 70° (Hirth et al. 1994). The jet is approximately orthogonal to the direction of linear optical polarization}, PA ~ 170° (Bastien 1982), and to the long axis of CO (2--}1) emission detected in aperture synthesis images of DO Tau, PA ~ 160° (Koerner & Sargent 1995). Kinematic models of the molecular line emission are consistent with the presence of a circumstellar disk that is centrifugally supported within a radius of 350 AU from DO Tau (Koerner 1994).

Here, we report on sub-arcsecond images of the $\lambda = 7$ mm emission from DO Tau which were made using the recently upgraded Very Large Array (VLA) of the National Radio Astronomy Observatory[1]. We have supplemented these measurements with continuum observations of DO Tau at other wavelengths to sample the spectral distribution emission from $\lambda = 1.3$ mm to 3.6 cm and improve our understanding of grain properties in the circumstellar material.

2. Observations and Results

The VLA was used to observe DO Tau in radio continuum emission at 43.3, 22.5, and 8.4 GHz ($\lambda = 7$ mm, 1.3, and 3.6 cm). The phase center was offset 1" in both RA arid Dec from the stellar position of DO Tau (Herbig & Bell 1 988), and the total bandwidth was 100 MHz in right and left circular polarizations. observations at 43.3 GHz were carried out on 1994 April 3 4 with the inner seven antennas of the high-resolution A configuration, and on 1994 August, 20 with 10 inner antennas of the B configuration. Baselines up to 5.6 km provided UV coverage in the range 30 800 kλ. On both dates, DO Tau was observed at 22.5 and 8.4 GHz using the remainder of the VLA's 27 antennas. UV coverage was 50 2700

[1]NRAO is operated by Associated Universities Inc. under cooperative agreement with the National Science Foundation.

kλ at 22.5 GHz and 20 1000kλ at 8.4 GHz. Absolute flux densities were calibrated using 3C48 and 3C286 with an estimated uncertainty of 20%. At 43.3 GHz, gain calibration was accomplished with periodic observations of 0333-1321 with a measured flux density of 0.98 $\pm$ 0.06 Jy. At 2'2.5 GHz and 8.4 GHz, the gain calibrator was 0400-I 258 with flux densities 0.65 $\pm$ 0.03 Jy and 0.83 $\pm$ 0.01 Jy, respectively.

Data calibration and mapping used standard routines in the NRAO AIPS software package. Daytime atmospheric phase fluctuations during A array observations necessitated extensive editing and application of a Gaussian taper to the UV data, resulting in a 0.68″ x 0.53" (FWHM) synthesized beam at PA --78". This corresponds to 95 $\times$ 74 AU at the 140 pc distance of the Taurus molecular cloud (Elias 1978; Kenyon, Dobrzycka, & Hartmann 1994). Fig. 1a displays the CLEANed image of DO Tau at 43.3 GHz. An unresolved source with flux density 1.80 $\pm$0.71 mJy is detected at the stellar position, $\alpha(1950) = 04^h35^m24.19^s$, $\delta(1950) = 26°04'54.5"$. The $\pm$0.71 mJy uncertainty includes rms variations in the map ($\pm$ 0.35 mJy bi"]) and a possible 20(X error in absolute flux calibration. At 22.5 and 8.6 GHz, 1)() 'l'au was not detected within the area encompassed by the 43.3 GHz synthesized beam to 3σ levels of 0.76 and 0.17 mJy, respectively.

observations were made with the Owens Valley millimeter array at 89.2, 111.2, 221.5, and 232.0 GHz (corresponding to $\lambda =$ 3.4, 2.7, 1.4, and 1.3 mm) between 1993 September and 1995 March. Measurements at 89 GHz were made with six telescopes; four were used at 110 GHz, and five at 220 and 230 GHz. overall IJ\~-ranges were 5 60 kλ (89 GHz), 5- 25 kλ (110 GHz), and 1055 kλ (220 Hz and 230 GHz). Resulting FWHM synthesized beams are listed in Table I. Antenna gains were determined from periodic observations of 0528+134 and absolute flux density calibration was based on measurements of Uranus. Data were calibrated using the Owens Valley software package, MMA, and mapped with AIPS. At all four frequencies, continuum emission is unresolved and peaks at the position of the VLA

43.3 GHz image. Aperture synthesis maps at 89 and 220 GHz are displayed in Fig. 1b and c. Measured flux densities at all frequencies are listed in Table I and displayed in Fig. 2.

3. Modeling and Discussion

Our measurements of DO Tau between 8.4 and 230 GHz can be fit by a single power law, $F_\nu \propto \nu^\alpha$, with index $\alpha = 2.39 \pm 0.23$, shown as a solid line in Fig. 2. Earlier detections of radio emission from TTs at wavelengths greater than 1.3 cm yielded values of α between 0 and 1 (Bieging, Cohen & Schwartz 1984) and have been attributed to free-free emission from ionized outflows (Reynolds 1986). Extrapolating from the upper limit of 8.4 GHz emission with $\alpha = 1$ (dotted line in figure 2), we estimate that no more than 49% of DO Tau's 43.3 GHz emission can arise as free-free radiation from an ionized jet. The millimeter-wave emission suggests that all the observed flux originates from circumstellar dust.

The frequency of the mm-wave dust opacity, β, can be derived from α, since $\alpha \approx 2 + \beta/(1 + \Delta)$, where Δ is the ratio of optically thick to optically thin emission from the disk (eqn. 1 of BS). At frequencies where emission from a circumstellar disk is largely optically thin and the Rayleigh-Jeans approximation holds, $\beta \approx \alpha - 2$. For DO Tau, continuum emission appears to be largely optically thin, even at sub-millimeter wavelengths (BS; Mannings & Emerson 1994). We derive an estimate of 0.39 ± 0.23 for β_{1-7mm}, in good agreement with the BS value of $\beta_{0.6-1mm}$, 0.4 ± 0.2. There is no evidence for the change in β longward of 2mm, cited by Mundy et al. (1993) for a few other TTs.

An estimate of β can also be obtained by fitting the spectral distribution of luminosity $L_\nu = 4\pi D^2 \nu F_\nu$ with a disk model which takes into account any contribution from optically thick emission. Following BSCG and Adams et al. (1990), we assumed power-law radial profiles in disk temperature and surface density, $T = T_0(R/R_0)^{-q}$ and $\Sigma = \Sigma_0(R/R_0)^{-p}$

with p = 1.5 or 1.75. The ll-lillill)ct,c:r-wave: emissivity of the grains was given by $\kappa = 0.1(\nu/10^{12} Hz)^{\beta}$ cm^2 g-'. The outer radius, R_d, was a llowed to lake on values between '22 and 350 All; the former is the lower limit to disk size if all $\lambda = 1$ mm emission is optically thick (11 S); the latter is the deconvolved half-maximum radius of the CO-emitting region (Koerner & Sargent 1 995). Aperture synthesis images of the CO emission suggest the inclination angle of the disk, θ, is 40° (Koerner & Sargent 1995). From the 12, 25, and 60μm IRAS fluxes, which probe optically thick regions of the disk, we obtain '1' = 218 K at 1 All with q = 0.54, very close to the value derived by BSCG for a face-on disk. Best-fit values of β and M_d, the total disk mass, were estimated from the minimum reduced χ^2 value. Acceptable fits, with χ^2 falling within $\Delta\chi^2 = 1$ of its minimum value, were found for the entire range of p and R_d values. The best-fit model, with $\beta = 0.6 \pm 0.3$, $M_d = 1,0 \pm 0.5 \times 10^{-2} M_{\odot}$, p = 1.75, R_d = 350 AU, and χ^2 = 0.77, is plotted in Fig. 3 as a solid line, along with the luminosity distribution derived from IR AS, sub-millimeter, and millimeter observations of DO Tau. These parameters yield A ≈ 0.28 at $\lambda = 3$ mm (using eqn. 20 of BSCG) and make possible a revised estimate of β from the power-law fit to data presented here. For A = 0.28 and $\alpha = 2.39$, we obtain $\beta = 0.504$ 0.23, in good agreement with the value obtained from the disk- model fit to the entire luminosity distribution).

For the ISM, it is commonly assumed that β is about 2 in the wavelength region considered here (Mathis 1990), although values as low as 1.3 have been obtained from laboratory studies (Agladze et al. 1994). Low values of β in T-Tauri dust disks have been inferred from sub-millimeter observations (BS; Mannings & Emerson 1994), but optical depth effects and insufficient spectral coverage introduced considerable uncertainties. The derivation for DO Tau is constrained by denser sampling at sub-millimeter wavelengths and wider spectral coverage at longer wavelengths. Nevertheless, we obtain a surprisingly low value of β, between 0.39 and 0.6.

A variety of physical and chemical explanations for low values of β have been proposed (Wright 1987; BS; Krügel & Siebenmorgen 1994; Ossenkopf & Henning 1994; Pollack et al. 1994), including grain growth (Miyake & Nakagawa 1993). If the average grain size is steadily increasing, reflecting planetesimal formation in the late T Tauri phase, β should decrease as disks age. However, DO Tau is relatively young, $\sim 6 \times 10^5$ yrs, with an outflow typical of an active disk, implying a very short timescale for grain growth. Recent 7 mm images of a source at a very early stage of protostellar evolution, IH124MMS, also yield a low value of β (Chandler et al. 1995).

Grain sizes of less than 1 mm could explain our value for β (cf. Miyake and Nakagawa 1993). Theoretical timescales for production of mm-size particles in the early solar nebula are quite short ($\sim$ 100 yr) (cf. Fig. 19, Cuzzi, Dobrovolskis, & Champney 1993), consistent with our observations. Other effects cannot be ruled out, however, and the value of β at a later planet-forming stage of disk evolution when dust is decoupled from the gas and settles into the plane may be different again, since collisions which lead to accumulation of planetesimals also generate a substantial population of smaller dust grains (Lissauer & Stewart 1993). Long mm-wavelength observations of a statistical sample of 'TT's with a range of ages are clearly required to address this problem.

We are grateful to D. Wood for assistance during the first season of 43 GHz observations at the VLA. D.W.K. acknowledges support for this work from NASA grant NGT-51071 and a fellowship from the National Research Council. The Owens Valley millimeter-wave array is supported by NSF grant AST-931 4079. Research by A.I.S. on protoplanetary disks is furthered by NASA grant NAG W-4030 from the "Origins of Solar Systems" program.

Frequency (GHz)	Flux Density (mJy)	Statistical error (mJy)	Total error (mJy)	Synthesized Beam Parameters B_{maj}	B_{min}	PA
8.4	<0.17 (3σ)	...	...	0.41″	0.38″	120°
22.5	<0.76 (3σ)	...	...	0.25″	0.23″	–10°
43.3	1.80	0.35	0.71	0.68″	0.53″	–78°
89.2	14.2	0.9	3.74	2.86″	2.10″	82°
111.2	30.2	4.5	10.5	13.0″	5.4″	–69°
221.5	98.6	4.9	24.2	3.98″	3.15″	62°
232.0	137.5	4.9	32.4	3.41″	3.15″	–84°

Table 1: Radio (VLA) and mm-wave (OVRO) Continuum Flux Densities from DO Tauri. Total errors include 20% uncertainty in the absolute flux density calibration.

REFERENCES

Adams, F. C., Lada, C. J., & Shu, F. 11. 1987, ApJ, 312, 788

Adams, F. C., Emerson, J.])., & Fuller, G. A. IWO, ApJ, 357, 606

Agladze, N. 1., Sievers, A. J., Jones, S. A., Burlitch, J. M., & Beckwith, S. V. W. 1994, Nature, 372, 243

André, P., & Montmerle, 'I'. 1994, ApJ, 420, 837

Appenzeller, I., Jankovics, 1., & Östreicher, R. 1984, A&A, 141, 108

Bastien, 1). 1982, A&AS, 48, 153

Beckwith, S. V. W., & Sargent, A. 1. 1991, ApJ, 381, 250

Beckwith, S. V. W., & Sargent, A. I. 1993, in Protostars and Planets 111, ed. E. 11. Levy & J. 1,. Lunine (University of Arizona Press: Tucson) 521

Beckwith, S. V. W., Sargent, A. 1., Chini, R. & Güsten, R. 1990, AJ, 99, 924

Bieging, J. H., Cohen, M., & Schwartz, P. R. 1984, ApJ, 282, 699

Chandler, C. J., Koerner, D. W., Sargent, A. 1. & Wood, D. (). S. 1995, ApJ, submitted

Cuzzi, J. N., Dobrovolskis, A. R., & Champney J. M. 1993, Icarus, 106, 102

Edwards, S., Cabrit, S., Strom, S., Heyer, 1., Strom, K., & Anderson, E. 1987, ApJ, 321, 473

Edwards, S., Ray, T., & Mundt, R. 1993, in Protostars and Planets 111, ed. E. H. Levy & J. 1,. Lunine (University of Arizona Press: Tucson) 567

Elias, J. 11. 1978, ApJ, 224, 857

Henning, 'I'., & Thamm, E. 1994, Ap&SS, 212, 215

Herbig, G. H., & Bell, K. R. 1988, in Lick Observatory Bulletin No. 1 I 11 (Univ. of california)

Hirth, G. A., Mundt, R., Solf, J., & Ray, T. P. 1994, ApJ, 427, L99

Kenyon, S. J., Dobrzycka, D., & Hartmann, L. 1994, AJ, 108, 1872

Koerner, D. W. 1994, Ph. D. Dissertation, California Institute of Technology

Koerner, D. W., & Sargent, A. I. 1995, AJ, in press

Krügel E., & Siebenmorgen, R. 1994, A&A, 288, 929

Lissauer, J. J., & Stewart, G. R. 1993, in Protostars and Planets III, ed. H. H. Levy & J. I. Lunine (University of Arizona Press: Tucson) 1061

Mannings, V., & Emerson, J. P. 1994, MNRAS, 267, 361

Mathis, J. S. 1990, ARA&A, 28, 37

Mundy, L. G., McMullin, J. P., Grossman, A. W., & Sandell, G. 1993, Icarus, 106, 11

Miyake, K., & Nakagawa, Y. 1993, Icarus, 106, 20

Ossenkopf, V., & Henning, Th. 1994, A&A, 291, 943

Osterloh, M., & Beckwith, S. V. W. 1995, ApJ, 439, 288

Pollack, J. B., Hollenbach, D., Beckwith, S., Simonelli, D. P., & Roush, T. 1994, ApJ, 421, 615

Reynolds, S. P. 1986, ApJ, 304, 713

Sargent, A. I., & Beckwith, S. 1993, in IAU Colloquium No. 140, Astronomy with Millimeter and Submillimeter Wave Interferometry, ed. M. Ishiguro & W. J. Welch, (Bookcrafters, San Francisco) 232

Strom, K. M., Strom, S. N., Edwards, S., Cabrit, S., & Skrutskie, M. F. 1989, AJ, 97, 1451

Wright, E. L., 1987, ApJ, 320, 818

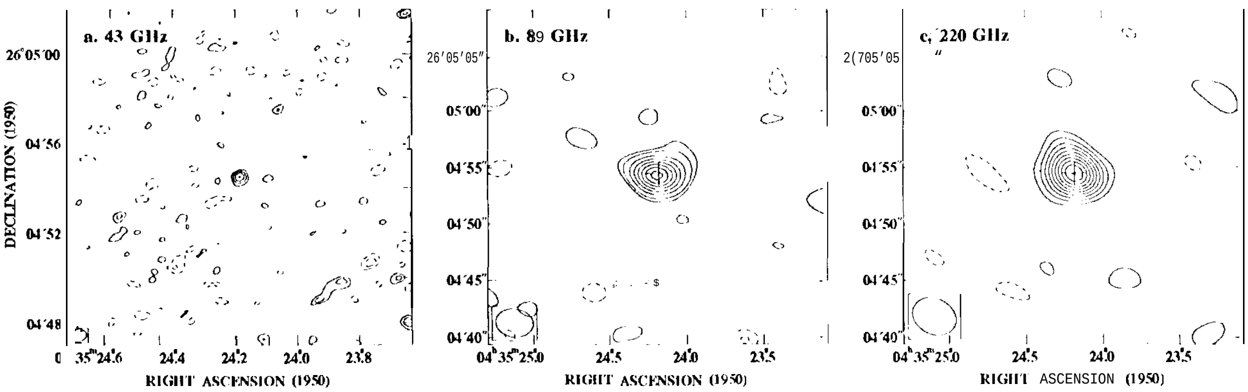

Fig. 1.- a) VLA image of DO Tauri at 43.3 GHz. Continuum emission is associated with the stellar position of DO Tauri. Contours are separated by 0.35 mJy (1σ), starting at the 2σ level; b) Owens Valley array map of 89.2 GHz continuum emission from DO Tauri. Contours are spaced at 2σ intervals of 1.8 mJy. The position of the 43.3 GHz emission is marked with a cross; c) Owens Valley array map at 221.5 GHz. Contours are at 2σ intervals of 9.8 mJy and begin at the 2σ level. At each frequency, the synthesized beam is shown in the lower left corner of the map.

Continuum **Spectrum of DO Touri**

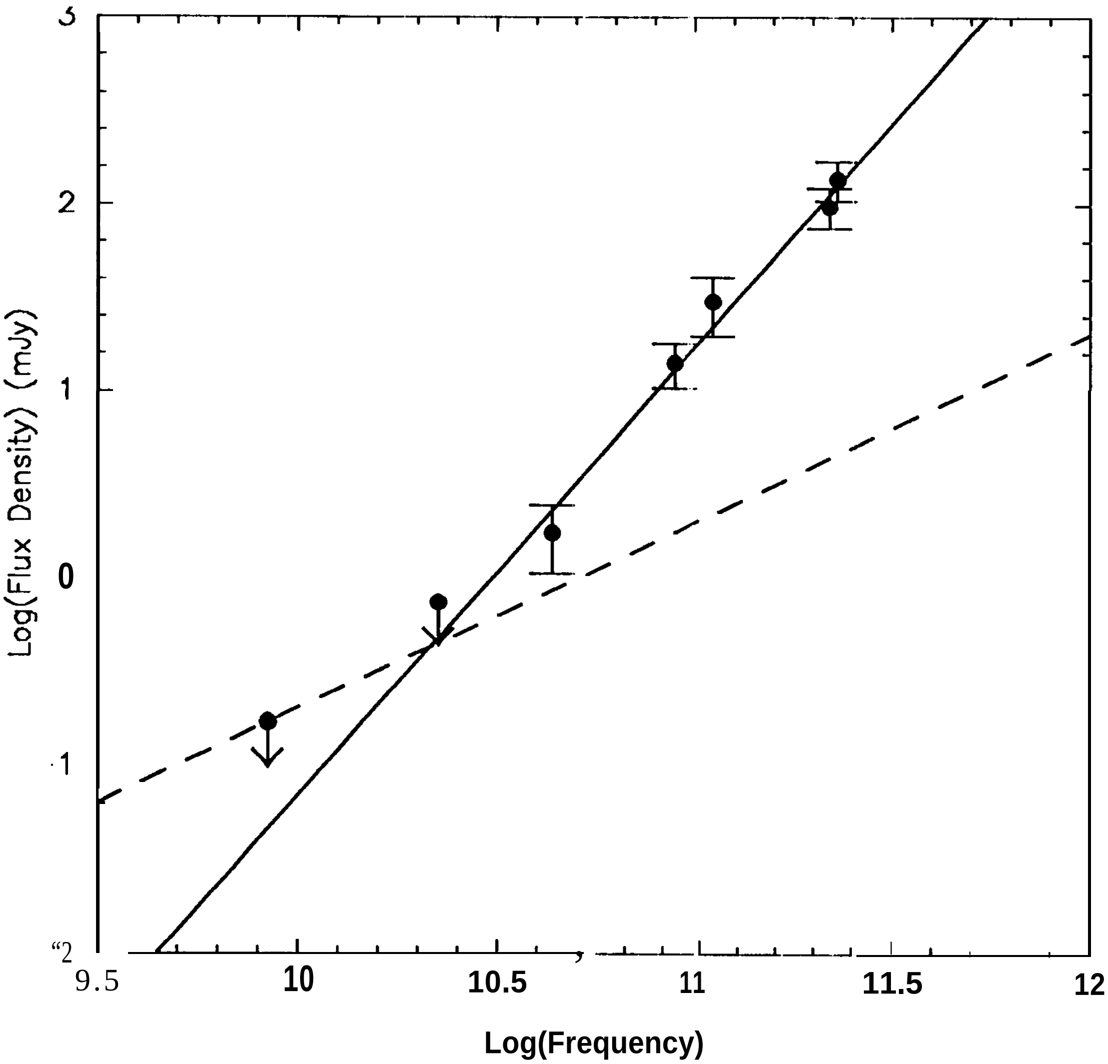

Fig. 2.- Continuum measurements of DO Tau as a function of frequency. Only upper limits are plotted at 8.4 and 22.5 GHz. A power-law fit to flux densities at 443, 89, 110, 220 and 230 GHz with spectral index α = 2.39±0.23 is shown as a solid line. The dashed line represents an extrapolation from the 8.4 GHz limit with α = 1.0, typical of an ionized stellar wind. The percentage of 43 GHz flux that could arise from an ionized jet is evidently less than 49%.

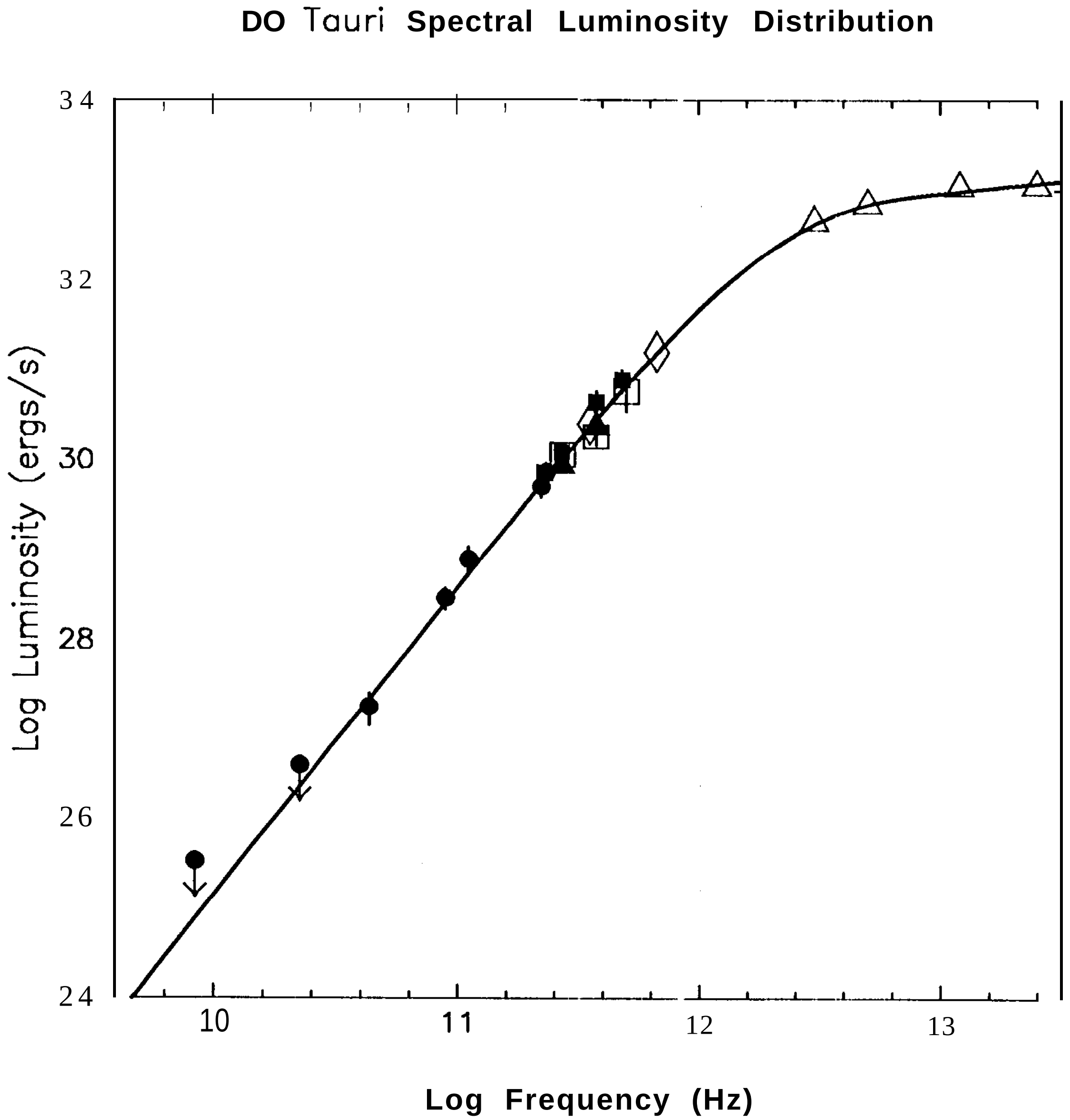

Fig. 3.- Spectral luminosity distribution of 1)() Tauri. Plotted measurements are from this work (find circles), BSCG and BS (find squaws), Adams et al. (1990) (open squares), Weintraub et al. (1 989) (filled triangles), Mannings & Emerson (1 994) (open diamonds), and Weaver & Jones (1 992) (open triangles). Error bars are shown only if larger than the symbol. The solid line represents the expected emission from a thin circumstellar disk with parameters as given in the text.